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SIDES AND THE BOTTOM OF RIVERS AND CANALS.

By CLEMENS HERSCHEL,

CIVIL AND HYDRAULIC ENGINEER, OF BOSTON.

REPRINTED FROM THE

JOURNAL OF THE FRANKLIN INSTITUTE,

For May, June and July, 1878.

PHILADELPHIA:

WM. P. KILDARE, PRINTER, 734 & 736 SANSOM STREET.

1878.

'8-8. July '3,
By the Author, of Boston

[Reprinted from the JOURNAL OF THE FRANKLIN INSTITUTE, for May, 1878.]

ON THE EROSIVE AND ABRADING POWER OF WATER UPON THE SIDES AND THE BOTTOM OF RIVERS AND CANALS.

By CLEMENS HERSCHEL, Civil and Hydraulic Eng., of Boston.

The title of this paper will recall to the minds of most engineers some well known, but, as will be shown, somewhat too highly valued observations of the "Ci-devant Colonel au Corps Royal du Genie," Le Comte L. G. Nançay Dubuat, who experimented 100 years ago—more exactly, between 1780 and 1784. To some it may also recall the fervent appeals of Mr. Thos. Login, M. Inst. C. E., 1867-69, in behalf of this same and but feebly illuminated branch of engineering and hydraulic science. Compelled to consider the matter, in the course of his professional practice, the writer has drawn freely upon all the German, French, English and American authorities within his reach; and, as showing the great utility and deciding influence which such a study may have in the consideration of water-courses, a concise history of the engineering problem referred to is here given; this is no less than that of the Cape Cod ship canal, in the state of Massachusetts.[1]

The Isthmus of Cape Cod, plainly to be seen on most any map, or globe, even, that represents the United States, is in effect nothing but a huge mole, or pier—a sort of fence run out into the sea, that separates the "Bay shore" of Massachusetts, and the sea-coast of Massachusetts, New Hampshire and Maine to the north of that, from the rest of the United States. But this is not all; navigation around this obstruction is of a very hazardous kind, because of the many and concealed shoals all along the route through the sound, and also on the outside of the islands of Martha's Vineyard and Nantucket; and from the fact that there is no harbor, not even for small coasters, between the southerly and the northerly ends of the Cape; further, because the sailing directions around this cape make less than a right angle with each other, because of the rigor of the climate in the winter, on account of the

[1] See also an article by J. P. Frizell, C. E., JOURNAL OF THE FRANKLIN INSTITUTE, 1871, on the same subject.

danger of collisions in the narrow channels between the shoals and in fogs, and from other such causes.

These difficulties may be measured by their effects, which comprise wrecks and losses of life and property to a remarkable extent. Thus, from 1843 to 1859, 17 years, there were 827 wrecks, of which a record could be found: 4 steamers, 40 ships, 71 barks, 191 brigs, 492 schooners, and 29 sloops; total losses, 500, partial losses, 327; average of the total losses (compiled from the records of 108 cases), $500,000 annually; average of the partial losses, $81,750 annually; loss of life, estimated at 30 annually.[1] For the ten years succeeding, 1859 to 1869, there were lost 13 steamers, 23 ships, 32 barks, 100 brigs, 446 schooners, and 3 sloops; total, 617 wrecks; total losses, 211, partial, 406. And all this on a length of steamer line of only about 160 miles. And, of course, these losses have their effect on the rates of insurance and the freight charges by vessels that pass the Cape.

It cannot be surprising, therefore, that the project of constructing a canal across the Cape should have frequently been spoken of, and, in fact, we find that ever since 1623, only three years after the settlement of the country by the prilgrims of Plymouth, the utility of going through or over the Cape, rather than going around it, seems to have been recognized, and that a canal has been contemplated for more than 200 years. It will not be necessary to give in this place a history of all the attempts that have been made to commence the construction of such a canal by public, as well as by private, means. Suffice it to say that 8 distinct efforts of this kind have been made, the last of these having been made in 1860. And now, lest any one will have found the explanation of this remarkable state of affairs in the topography of the country through which the canal is to pass, it will be proper to state at once that this topography is of the most favorable description. There is a valley running through the Cape at its narrowest part, precisely where it joins the mainland, at the head of "Buzzard's Bay," and where the distance from bay to bay, on line of this valley, is about seven miles and a half. The bottom, or intervale, of this valley, is some 600 ft. wide at its narrow est part, and is, in maximo, about 32 ft. above the controlling mean low water of the sea. The meaning of this phrase, "controlling" mean low water, being, that low tide in one bay is at a different eleva-

[1] From the report of the Legislative Committee of 1864. Some wrecks are included which should have been omitted; others were, no doubt, omitted, of which no record had been kept.

tion from what it is at the other, and the lowest low water is naturally the "controlling" low water. The average depth of cutting, for a canal 18 ft. deep at controlling mean low water, would be only about 35 ft. The material, as shown by borings to the proper depth, and from all the other information that can be reached, is, throughout, nothing but mud, sand, gravel, and a few boulders. Two tidal creeks occupy this valley, and their head-waters nearly overlap each other. Every report that has ever been made upon this project has spoken of it in highly favorable terms, and has estimated that the enterprise would be a profitable one, viewed from a national and political-economical standpoint. Why, then, has this canal never been built? Why has it not been built since 1860-64, date of the last investigation upon the subject by the state of Massachusetts?

Of course, the answer to these questions may be variously enunciated, but a tolerably fair one to the last of the two questions may be given, though it seems almost laughable to say so, by reference to only these two sentences in the report of 1864: "We have already spoken of the locks required, in consequence of the different levels of the sea at the two extremities of the canal. The mean of the daily maximum variations in the elevations of the two basins" (occurring 4 times in the 25 hours) "is 6·5 ft." (should have been 5·23 ft.); "and such a fall in the distance of eight miles, must, we need not say, be kept under control." Further than by these words, the *question*, whether or not locks were a necessary part of the plan, was nowhere discussed, but it was *assumed*, as by the last phrase in the second sentence above quoted, that canal locks were unavoidable. But the same report takes care to say that the current to be produced in the canal will not be detrimental to navigation; it "would not exceed from three to four miles per hour; it sometimes reaches nearly three miles per hour off West Chop, where the tide-waves cross each other in eleven fathoms of water." The report quoted from is a preliminary report, made by an "advisory council," and the inference is irresistible that the only reason that the advisory council assumed the necessity of, and recommended, locks, and all the evils that these entail, was on account of the supposed destructive effects which those currents were going to have upon the sides and bed of the canal. Subsequent engineers made the same assumption, and the fears so engendered have remained alive to the present day; so that it is yet impossible to speak of the Cape Cod ship canal to any merchant or other otherwise intelligent person in Massachusetts, without hearing

it answered, that owing to the necessity of locks, breakwaters, etc., the cost of such a canal would be something quite tremendous and altogether impracticable.

This leads to the consideration of what have above been referred to as the evils entailed by the plan of having locks, or a lock at either end of the canal. First, as regards an increase of cost: 1. The cost of the locks themselves, which, to accommodate, as they would have to at the present day, some 40,000 vessels per annum, would have to be built in triplicate and quadruplicate form, and, from their size, would cost large sums of money to build and to operate. 2. Since the locks at the northern end would stand upon an open seashore, on a sandy beach, they would require highly expensive works for their protection, and for the protection of vessels about to use them. It will not be necessary to enlarge upon either of these points, as they will be sufficiently appreciated by all engineers of the present day. Suffice it to say that the estimates for the two kinds of canal—the one an open cut, with jetties at the northern end to lead to deep water, the other with locks and breakwaters and jetties—compare about as 1 to 4; that is, as 2 millions of dollars to 8 millions. Secondly, comparing the two plans as to their probable income: 1. The canal is most needed in the winter, that being the most dangerous season of the year for navigation, when many coasters absolutely decline to take freights from New York, and further south, for Boston, and further north. But it is precisely then when a canal with locks would be out of service, being frozen up. On the other hand, there are good reasons, which need not now be gone into, for believing that an open cut, a "cut-off," speaking after the manner of river engineering as applied to tidal waters, would remain open all the time, especially when used by steam navigation. 2. Less detention and danger to vessels in passing through an open channel, than in passing through locks; hence greater use of the canal in the one case than in the other. 3. Less cost of haulage, or of steaming through the canal in the first case than in the second. A vessel could drift through with the tide in about three hours, and could drift either way twice every 25 hours; and naturally this drift of the current would work to the advantage of the steamer quite as much as it would to that of the sailing vessel. So that taking it altogether, it is within the mark to say that the plan with locks is simply out of question as a remunerative enterprise. Where the first would be a highly profitable

investment for private capital, the other may reasonably be shunned by even a paternal form of government; and has been shunned and has rested *in terrorem* in the minds of those interested for the past fifteen to seventeen years, ever since that unfortunate dictum—"such a fall must, we need not say, be kept under control"—and its resultant plans and estimates, and report of 1864.

To complete this sketch, and before examining the hydraulic question given in the title of this paper, it will be well to give, in concise form, the heights of tide that obtain at either end of the proposed canal, as carefully determined by observations of Henry Mitchell, the present Chief of Hydrography of the U. S. Coast Survey, in 1860-62. The table below will be all that is necessary; the heights read above (+) and below (—) the mean level of the sea, which is the same at both ends of the canal. This level is called grade 52·7 in the report.

The channel or preliminary cutting for which the velocities given in the table have been computed, for several times of the tide, has its bed about 20 ft. below the mean level of the sea at the southern end, and about 22·5 ft. below it at the northern end. It is 66 ft. wide at the bottom, and has temporary side slopes of 1·25 on 1, making the water-line from 111 to 134 ft. wide. The velocities given have been computed by Hagen's formula for *large rivers and canals*, this formula having been selected on account of its great convenience in use, and simplicity, while it remains, at the same time, a very reliable formula for large rivers and canals; but those who may prefer any other formula will readily see that the present is not one of those cases where a difference of ten and of even more per cent. in the resultant answer will be of consequence. The average skipper cares very little whether he has to tow against 3·3, or 3·6 or 3·7 knots per hour for a distance of 7·5 miles. The bottom velocities are calculated from the simple rule given by Schlichting, derived from Hagen's formulæ, and exactitude in their case, within about 10, or even 25, per cent., may also be shown to be of no serious import. These formulæ are:

$$\text{Mean Velocity} = 6 \,.\, \sqrt{\frac{\text{Area}}{\text{Wetted perim.}}}\ \sqrt[5]{\frac{\text{Fall}}{\text{Length}}},\quad \frac{\text{Mean Velocity}}{\text{Surface Velocity}} = 1 - 0{\cdot}0326\,\sqrt{\text{Depth}};\ \text{and Bottom } V. = 3 \text{ Mean } V. - 2 \text{ Surface } V.$$

If this sketch has served to give a rude description of the locality and canal, during the study of which the materials for the balance of

SIMULTANEOUS TIDAL OBSERVATIONS AT TERMINI OF PROPOSED CAPE COD CANAL, AUG. 14, 15, 1860, AND COMPUTED CURRENTS THROUGH CANAL.

Hour.	Height of tide in ft. at the northerly terminus.	Height of tide in ft. at the southerly terminus.	Fall in ft. on a length of about 40,000 ft.	Direction of current	REMARKS.	CURRENTS. Mean Velocity. Feet per second.	Surface Vel. Feet per second.	Surface Vel. Miles per hour.	At bot. and sides. Feet per sec.
0	—1·2	—1·6	0·4	S.	Nearly highest spring tides.				
1	—3·2	—1·0	2·2	N.	Fall = 0 at 0 h. 10 m.				
2	—4·7	—0·6	4·1	N.	L. W. northern end, at 2 h. 25 m., when fall = 4·5.				
3	—4·5	—0·0	4·5	N.					
4	—3·7	+1·1	4·8	N.		3·7	4·3	2·9	2·5
5	—2·2	+1·55	3·75	N.	H. W. southern end.				
6	—0·45	+1·35	1·8	N.	Fall = 0 at 6 h. 50 m.				
7	+1·2	+0·8	0·4	S.					
8	+3·0	—0·2	3·2	S.	See Note.	[4·3]	[5·0]	[3·3]	[2·7]
9	+3·7	—1·2	4·9	S.	H. W. northern end.				
10	+2·9	—2·1	5·1	S.					
11	+1·4	—2·3	3·7	S.	L. W. southern end.				
12	0·0	—1·6	1·6	S.					
13	—1·95	—1·05	0·9	N.	Fall = 0 at 12 h. 35 m.	2·5	3·0	2·0	1·7
14	—3·75	—0·4	3·35	N.		3·3	3·8	2·6	2·2
15	—4·3	+0·4	4·7	N.	L. W. northern end.				
16	—3·3	+1·6	4·9	N.		3·7	4·3	2·9	2·5
17	—1·4	+2·4	3·8	N.	H. W. southern end at 17 h. 40 m.				
18	+0·7	+2·6	1·9	N.					
19	+2·8	+1·9	0·9	S.	Fall = 0 at 18 h. 45 m.	2·8	3·3	2·2	1·8
20	+4·5	+0·5	4·0	S.		3·7	4·4	2·9	2·4
21	+5·5	—0·8	6·3	S.	H. W. northern end.	4·1	4·8	3·2	2·6
22	+4·9	—1·7	6·6	S.	Max. fall = 6·7 at 21 h. 40 m.				
23	+3·1	—2·1	5·2	S.	L.W. southern end at 23 h. 20 m.				
0	+1·3	—2·0	3·3	S					
1	—1·1	—1·8	0·7	S.	Fall = 0 at 1 h. 10 m.				

Mean fall in 25 hours = 3·43 ft. [irrespective of direction].

NOTE.—Calculated for a fall of 8 ft. and full canal—an extreme case.

this paper were gathered, and has served to show at least one instance where the application of such study would seem to be of decided and decisive character, it will be proper to proceed now with the consideration of the purely engineering question of the determination of the effect of running water upon the sides and the bottom of rivers and canals.

The way that has usually been followed in this particular species of investigations, hitherto, has been to find formulæ derived from series of experiments that give, from the cross-section and slope of any channel, its mean velocity; then another set that enable the surface and the bottom velocities to be arrived at; then find by experiment the effect of certain velocities on certain substances, generally in very small quantities, and resting upon smooth horizontal plank; upon which, nothing so plain, but that such and such slopes of water will carry away such and such banks and beds of the channel. It affords a healthy check, however, on these conclusions, to compare them with what we see going on around us, of this sort of action, both in rivers and in artificial channels; also not to stop the investigation with the mere *starting* of the kinds of channel surface under discussion, but to pursue the investigation a little further, and see what will take place next, and to consider the extent of such action; for, although a canal in embankment might be endangered by such operations, another, entirely in excavation, may be greatly improved by the same scouring process.

The present paper does not pretend to solve, however imperfectly, the question here presented; this could, of course, only be done in the light of extensive and well conducted experiments. Many investigators are at work in solving the problem of velocities of rivers and canals, and the distribution of velocities in any cross-section, and in that part of the general question we may, sooner or later, feel that we are standing on an unassailable foundation of knowledge, at least in the case of perfectly regular channels. In the meantime, and in default of any very decisive experiments made as yet upon the actual effect of large streams or canals upon their beds, the best immediately attainable results are those that may be derived from a compilation of such data as are recorded in engineering literature. To do this has been the essay of the following pages.

Engineering literature on the erosive or abrading power of water may be divided into three classes: 1. Experiments on the effect of

running water upon substances of various sizes and weight in artificial channels. 2. Facts to be observed in natural streams. 3. Discussions of the facts derived under the heads just cited. As some writers have done service in all three of these methods, the division will not always be followed out, but it is well enough to have it thus stated at the outset, for a better understanding of the whole subject.

Dubuat[1] [1780-84] seems to have been the first writer on the effect of currents upon the bed of the channel, who gave facts and figures, and is quoted to this day more frequently than any other experimenter. In the course of the 91 years that have elapsed since the first appearance of his book, his remarks have been translated and quoted back and forth so many times, that their original import, and weight as testimony, are hardly discernible, and it is very instructive to refer back to just what Dubuat said on the subject matter of this paper, and to consider his description of the experiments made by him.

Dubuat thought that he had found a constant relation between the mean, surface and bottom velocities of any stream, and that this was expressed by the formulæ:

$$V_D = \left[\sqrt{V_o} - 1\right]^2; \text{ and } V_m = \frac{V_o + V_D}{2},$$

using the Humphrey-Abbott notation, where V_m, V_o and V_D represent the mean, surface and bottom velocities (Sec. 66, Dubuat). These are the formulæ used by Beardmore in his Manual of Hydrology, to compute Table 3. It is high time, however, to acknowledge and recognize that these formulæ are nothing but a first approximation, and that they are deserving of no especial confidence at the present day.

Dubuat used in his experiments two rather diminutive troughs made of plank (see the plate in Vol. 2), one rectangular in section, and about 18 in. × 12 in., inside measurement; the other trapezoidal in section, about 6 in. wide at the bottom, side slopes about 1⅜ on 1, and water about 8 or 10 in. deep; their length is not given. Dubuat only says he should have *liked* to have made them 500 or 600 ft. long. Besides this he made 6 experiments on a canal varying from about

[1] "Principes d'Hydraulique et de Pyrodynamique." Nouvelle edition. 3 vols. Paris, Firmin Didot, 1816. (First edition appeared in 1786.)

DUBUAT'S TABLE OF RESULTS, AS GIVEN IN HIS VOL. 2, § 399. [COLUMNS 2 AND 3 ARE ADDED.]
SEE, ALSO, DUBUAT, VOL. 1, § 71.

Description of Substance.	Estimated Diam. Inches.	Specific Gravity.	Velocity of Current at the Bottom in Feet per Second.									
			0 25	0·33	0·50	0·60	0·67	1·00	1·46	2·00	3·00	3·75
Brown clay fit for pottery	?	2·64	Stands	Deposits fine sand	Deposits fine sand	Carried off	....	....	....	....	....	....
Coarse yellow sand	?	3 36	Stable	....	....	Stable	Stands	Carried off	....	....	....	....
Seine gravel, size of anise seed............	0·04	2 545	Stable	Stands	Carried off	....	....	....	....	....	....	....
Seine gravel, size of pea at most...........	0·2	2·545	Stable	....	Stable	Stands	Carried off	....	....	....	....	....
Seine gravel, size of a little bean............	0 4	2·545	Stable	....	....	....	Stable	Stands	Carried off	....	....	....
Sea shingle rounded, at the most 1 in. diam.	1·0	2·614	Stable	....	....	....	....	....	Stable	Stands	Carried off	....
Flints, angular, volume of hen's egg....	1·5	2·25	Stable	....	....	....	....	....	....	Stable	Stands	Carried off

48 to 127 sq. ft. in section, and 4 experiments on a small river, varying from about 241 to 310 sq. ft. in section; both very shallow, only about 1 to 2 to 3 ft. deep, and 3 of these were rendered unreliable by untoward circumstances, as detailed by Dubuat himself. Nevertheless, these spoiled experiments, and the others, are to this day occasionally used by the constructor of hydraulic formulæ. All the experiments were conducted in a tolerably crude manner, looking at them in the light of the much more carefully and exactly conducted ones of later times, the velocities being generally measured by little wooden and other floats (gooseberries for measuring bottom velocities), levels taken by measuring down from pegs, etc., so that, taken altogether, if the whole of Dubuat's experiments were dropped out of all future consideration, it would no longer be a serious loss to science; indeed, to consider them, and give them the same weight with many more perfectly derived ones of later days, in the study or derivation of formulæ, they cannot but be looked upon as decidedly unscientific, and resembling, in some degree, that celebrated "survey" of the American humorist, John Phœnix, Esq., who averaged the distance as given between two places, by a peculiar sort of triangulation, of astronomical observation, and of direct chaining, and by casual estimate of a bystander, as the best result attainable.[1]

The same little troughs mentioned above, served for the experiments on the "abrading and transporting power of water," the *rolling* along of gooseberries giving the bottom velocities. These results of Dubuat's experiments are best given in the table of Vol. 2, Sec. 399, though they are also stated in words, somewhat incompletely translated, as usually quoted, in Sec. 71 of Vol. 1.

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[1] To discuss, as part of the general question, the subject of what is called the "scale of velocities" in currents, and the dependence of the mean or surface velocity upon cross-section and slope, and to bring such discussion to date, would extend this paper to the size of a comprehensive treatise on hydraulics. The writer cannot venture upon this field of labor at this time, and, in place thereof, may leave, without argument, to each engineer the use of such well founded formulæ as seem best to him. That there is no one formula, or no one set of formulæ, that commands universal respect and confidence among engineers, is much to be regretted. Just at present, this matter is in a peculiarly deplorable state, from over-zeal of writers to evolve something new, in the first place, and absolutely exhaustive, in the second, and without due regard to a proper study of the subject, or to the quality of the data which they recklessly throw pell-mell into their formula-producing chaldron.

Dubuat also pursued the inquiry somewhat further, and observed what became of the sand after it had started. His Sec. 72, Vol. 1, is very interesting on this point. Says he: "When the velocity on the bed of the stream is great enough to cause bodies heavier than water to roll or slide along, these bodies are not moved along with uniform velocity, but they travel, as it were, by relays. Let us take the sand for example. When the bottom of the channel is composed of sand, a little coarse and well visible, and the velocity there is 0·67 or 1·00 ft. per second, its appearance resembles that of what is known as Hungarian lace, forming irregular furrows at right angles to the current." Then he goes on to describe the well known wrinkles to be observed in all sandy streams, and how the sand rolls up the flat upstream slope, and rolls over the crest, down the steeper downstream slope of these furrows, to be buried up by the next grains of sand, and so on.[1] "In this way," he says, "as a mean result the same grain of sand requires two years to travel 3 miles. If the velocity increases, it goes faster, if it diminishes, it will go slower." The statement is sometimes met with, that Dubuat said that a velocity of 2 feet per second made sand travel, in the above way, about 10 miles per annum. The only authority the writer has been able to find for this is the remark of Dubuat, that in the river Hayne it took sand 2 years to go from Mons to Condé, about 20 miles apart, and the average of the 4 measurements of the Hayne velocities given in the book is about 2 ft. per second at the surface and centre of the stream, varying from 1·33 to 3·00 ft. per second. But the value of this statement may be somewhat shaken in the minds of some, when introduced, as in the original, by this remark, Sec. 400, Vol. 2: "This river does not erode sand itself, for it flows in a clay bed, ordinarily; but at Mons they are in the habit of sanding the floors, and then they sweep the sand into the streets, where it is left in little heaps; the rain washes these into the river, whence it is carried, little by little, down to Conde, requiring apparently more than 2 years to go this distance, which is about 21 miles." Dubuat must be credited, however, with having recognized that his experiments were but a beginning, and that they should not be rated too high—a piece of warning that the three subse-

[1] For an example of the same thing on a very large scale, and in nature, see the report of Genl. G. K. Warren, U. S. Engrs., on "Fox and Wisconsin Rivers Improvement," Report of Chf. of Engrs., U. S. Army, 1876. Also separately printed; p. 73 of this edition.

quent generations seem to have neglected to a surprising degree. Says he, Sec. 396, Vol. 2:

"It is only by studying the course of the rivers of a kingdom, or even of all the different parts of the earth, in a thorough manner, that one could flatter himself to have gathered sufficient observations to be able to assign the proper degree of tenacity to every species of earth, and to determine the proper velocity of any stream, so that it shall neither erode its bed, nor form deposits. There is so great a variety in the combinations of the different materials which constitute the bed of a stream, that there cannot be any general rule for the determination of this velocity. Intelligent travelers would render a great service to science, if they would carefully observe the velocity at the surface of the different rivers of the earth, their mean cross-section, and the nature of the soil in which they flow. But observations of this kind cannot be made and gathered together, except in a great length of time, and it seemed proper to make at least an attempt in this direction, by the use of our experimental canal. It is with these views that we undertook the experiments now about to be described."

Robison's Mechanical Philosophy, about 1800, is often quoted from by English writers; but Dr. Robison, not having had opportunity to experiment, was obliged to confine himself to a discussion of the results found by Dubuat; and so with a host of other writers, who have repeated Dubuat's data for the movement of clay, sand, gravel, size of aniseed, peas and beans, one inch in diameter and the size of a hen's egg, in two little plank troughs, the bottom velocity being measured by the *rolling* along of some gooseberries that happened to be handy at the time, until it has become heresy to doubt any conclusions that may or may not be drawn from them. Dubuat's own words, quoted above, should teach us in which direction the path of duty lies.

The next writer in order of time, who gave the profession original data, was probably Umpfenbach, towards the end of the eighteenth or beginning of the nineteenth century. In default of the original work, the data given by him are here reproduced from an article by Prof. Sternberg, of Carlsruhe, Baden, which appeared in the *Zeitschrift für Bauwesen*, 1875, p. 495. Umpfenbach is there reported as having observed, following the hint given by Dubuat, perhaps, that when the velocity, at the surface and in the centre of

"small brooks," was as given in the first column, the diameters of the pebbles, of which their bed was composed, were as in the second column.

Max. Surface velocity in "small brooks." Ft. per sec.	Diam. of pebbles. Inches.
3·1	1·0
5·2	2·0
7·1	7 0
10·0	12·5
15·0	15·5

In the same article is found this statement made by Funk, also one of the earlier German writers on practical hydraulics, who generally wrote concerning the Weser, when he spoke of rivers, that with a maximum surface velocity of 5·6 ft. per second, the bottom was composed of granite shingle 2 ins. in diameter.

Somewhere about this time, 1820 odd, originated the formula given in "Stevenson on Harbors," page 157, quoted from Sir John Leslie; $v = 4\sqrt{a}$, "where a denotes, in feet, the side of a cubical block of stone, or diameter of a boulder, and v equals the velocity of the water in miles per hour, which is capable of moving it along the bottom." But really, if any one will refer to the original, page 392 of Prof. Leslie's "Elements of Natural Philosophy," Edinburgh, 1823, he will hardly thank Mr. Stevenson for having encumbered our harvest with this well intentioned, no doubt, but not very valuable bit of chaff among the grain. It is a formula that is evolved from purely theoretical reasoning on the impact of water, etc., and is finally modified by liberal assumptions. Taken altogether, the final conclusion left in the mind of the student, is that this formula may or may not represent the relation between velocity and size of cube, or sphere. [The formula is evolved for a cube, and it is then stated that it will be "nearly the same" for a sphere.] It will be better, not to consider it all in conjunction with the results of experiment, even when these latter have been somewhat crudely conducted.

The experiments of Dr. G. Hagen, (late "Ober-Landes-Bau-Director,") Chief of the Engineering Department of the Prussian Kingdom and its Provinces, come next, perhaps, in order of time.[1]

[1] See "Handbuch der Wasserbaukunst," in three parts, ten volumes in all. First two parts on water-sources, water-works, foundations, rivers and canals, in the third edition (1871–74.) Third part, works upon the sea, first edition, 1864. Berlin, Ernst & Korn.

The works of this writer do not seem to be so well known to English and American engineers as they ought to be; but they are standard works in Germany. As an engineer of some fifty years' experience, who commenced his career under the severe schooling of the well known astronomer, Bessel, and who has made it his aim to introduce into the study of engineering principles the same careful weighing of scientific testimony that has produced such marked results in the study of astronomy, anything said by Dr. Hagen on matters of engineering, merits the close attention of the reader.

Says he, Article 21, Part II, 3d edition: "I made the attempt to repeat them [Dubuat's experiments], using various kinds of sand, but I could not discover that there was any definite relation between the velocity and the ease with which the various sizes of sand were set in motion; at certain places where the cross-section was smaller, and hence the velocity was greater than at other places, the sand lay perfectly solid, and had been heaped up, while it had been washed away from the places last named. In large rivers, also, cases may frequently be found which confirm the experience last cited, and which show no erosion by the water, but, on the contrary, an increase of shoaling in those cross-sections wherein the mean velocity is evidently a maximum." And § 7: "In natural channels of rivers, there are many places which are notably deeper than the rest of the river, the ('pools'); one would think that these pools ought to fill up with particular rapidity on account of the decrease of velocity which they occasion, but such is not the case, and their depth remains the same, even though the pool should change its precise locality. On the other hand, there are places which have always been known as shoals and bars; they have repeatedly, and some of them have at every low water been dredged out, and yet every flood will deposit stones and sand anew in them." And in Article 8: "It is of great importance to know *in what manner it is that the water erodes the banks;* without doubt, this requires the expenditure of a certain amount of force, and this can only be generated by the motion of the water. It may be assumed, therefore, as a general proposition, that the action of the river will be greater, the greater its velocity. This is confirmed by experience, but it nevertheless remains questionable whether a *uniform* and rapid current will erode the banks; that is to say, a current in which the particles of water move parallel to the banks with a certain velocity; or whether this is not a matter less of

velocity of the whole mass of water, and more of the partial and *inner movements* of the particles among themselves, and of the *whirlpools* which are known to consume a certain portion of the vis viva of the moving water. All experience tends to confirm this latter assumption; it may be doubted only in so far, that both kinds of movement of the particles among themselves, and of them altogether in line of the current, increase and decrease, the one with the other, so that it cannot be decided which of the two was the cause of the erosion that has taken place." And the subject is further discussed philosophically and at length in Article 21. These are strange sounding words to the orthodox believer in the motion of water in straight lines or "filaments," to the devotee of "fluid veins," and of horizontal "layers" of water under all circumstances; but these notions, also, it is time were rudely shaken, especially in English literature upon the subject. It will no doubt be universally recognized before long, that it is only in the case of small and extremely regular-bodies of flowing water, if at all, that these notions can be made to apply. But in natural streams such conditions rarely exist, and the artificial canals, and even pipes, that have the regularity of experimental channels, are few indeed.

These inner irregularities of motion, just spoken of, were, however, studied so early as 1791, by Venturi,[1] at Modena, whose experiments were published in Paris, in 1797, under the title "Récherches experimentales sur le principe de la communication latérale du mouvement dans les fluids."

On page 165 of the "Tracts on Hydraulics," this lateral communication of movement in fluids will be found discussed in its application to rivers, and it is more than hinted at that this is the prime cause of the erosion of the bed and the shores of rivers.

In 1848 was published a book by J. Dupuit, an eminent engineer of the "Corps des Ponts et Chaussées," and an original thinker and writer on various engineering subjects, entitled "Études Théoriques et Pratiques sur le Mouvement des Eaux Courantes," which has since appeared in a second edition. Says M. Dupuit, in the preface, page xi: "We have attempted to prove by numerous examples that these sort of questions are eminently complex; that their solution depends

[1] A translation of Venturi's works, in Nicholson's "Journal of Natural Philosophy," vol. iii, London, 1802. Also in "Tracts on Hydraulics," by Thomas Tredgold, 2d edition, London, 1836.

on a great number of local circumstances of various elements, which can neither be expressed nor combined mathematically. Mathematics is to the engineer what grammar is to the writer; it may direct ideas and inventions, but it cannot produce them. The phenomenon of the transport and the deposit of alluvial matter is explained to-day either incompletely or erroneously. We present a new theory upon this subject. We show that there are two distinct forces at work in every stream flowing upon a bed that is subject to erosion; the power of dragging along the bottom materials, which depends on the absolute velocity of the stream, and the power of suspension of the stream, which depends upon the relative velocity of the various filaments among themselves." To the elucidation of this matter, M. Dupuit has devoted the last twenty-two pages of his work, which are to be commended to the student of this branch of practical hydraulics. Says he, page 230, first edition: "If we are to be guided by a few experiments of Dubuat, according to which it would result that for a velocity of 0·30 m. (1 ft.), sand will move at the rate of 2 kilom. (1·25 miles) per annum, and for a velocity of 0·60 m. (2 ft.), it would travel only 13 (8·25 miles), we should say that this power of dragging along, which could, in course of time and by constant action, produce very appreciable effects at any one definite point of the bed, cannot produce anything but very feeble effects upon the whole length of the channel. For we are speaking now of a layer of sand exceedingly thin, and moving with a velocity which is almost inappreciable. But however that may be, there is another force residing in the water which is much more powerful against movable materials, and which has not been sufficiently considered, it seems to us. This force, which we have called the power of suspension, reveals itself in a multitude of phenomena, which leave no doubt of its existence nor of its energy.

"'Gravel is transported not only upon the bed of a stream,' says M. Minard ("Navigation des Rivieres," p. 17), 'but also is elevated and is thrown upon the shores. The dykes of the Garonne are sometimes broken during floods, and after the subsidence of the water, volumes of 6000 to 8000 cubic metres of gravel are found on the recently cultivated territories. I have seen such masses of sand, which, after having passed through breaches in the dykes on the Loire, were two or three metres higher than low water of the river.' And we could, if there were need of it, confirm what M. Minard says

by similar facts observed upon the Loire; but it seems to us that they are too well known to be denied.

"Since deposits are formed upon the shores, two or three metres above low water mark, and consisting of enormous masses of gravel and of sand, it is very evident that this gravel, this sand, has been in suspension in the water; for gravel and sand dragged along the bed of the stream could not pass the breaks in the dykes and place itself in masses upon land, which is several metres higher than this bed. No other explanation is possible for this phenomenon than the one given of the suspension of the solid matter in the water of the stream. Besides, it is easy enough to convince one's self of this property of liquids and of fluids, by excessively simple experiments; we said fluids, just now, because gases have the same property: witness the elevation by the wind of clouds of dust, and in gravelly countries carrying even gravel to a great height and producing effects entirely analogous to those that have been cited." Then after explaining how it is that a difference in the velocity of contiguous filaments or small portions of a large stream of water can move a body floating upon the surface, laterally, M. Dubuit says: "The difference in the velocity of the filaments in making unequal currents pass to the right and to the left of the floating body, engenders a power which will push it towards the filaments that flow with the greatest rapidity. This is confirmed, moreover, by daily experience: a floating body tending to detach itself from the shores and to reach the thread of the current. If we should now imagine a solid body plunged into a stream, we shall see that the relative velocity of the filaments, in a vertical, will engender a similar kind of pressure, tending to push the body towards the most rapid filaments, that is to say, acting from below upwards." And after further discussion, the results of the investigation are thus summed up: "Flowing water can hold bodies in suspension which are much more dense than it. The power of suspension depends upon the relative velocity of the filaments, and is greater, the greater this relative velocity is. Generally speaking, it varies with the quantity:

$\frac{dv}{dz} = \left[\frac{\text{diff. velocity}}{\text{diff. depth}}\right]$, so that the lower planes of the stream can carry more voluminous solids, or more of them, than those higher up."

The power of suspension of any layer is limited, that is to say, a square metre of that layer can contain only a certain number of solids of a certain size. Thus, each layer has its own different degree of saturation. It is then explained why a shallow brook will run clear at a velocity, which in a deep river might *lift up*, not roll along, sand and gravel; how it happens that rivers deposit finer and finer materials from their sources downwards; why pools are not filled up, and shallows deepened, and more of the same sort.

Mr. Thomas Login, Mem. Inst. C. E., in the *Artisan*, 1869–32, also speaks of the whirling or rotary motion of water as effecting scour. Says he, in speaking of the way in which bridges and other works that guide water should be built, in order that they may not cause the water to undermine their foundations, the engineer "must take care that the water flows off smoothly, that is, that there be as few eddies as possible on leaving the works; but as this rolling or whirling motion cannot on all occasions be avoided, a slight increase of sectional area is necessary. Again, in nature, we never find that water flows in straight lines, but has either a whirling, or what appears to be a rotary motion, that is, any particle of water moving down a stream would follow the course of any point on the perimeter of a carriage wheel rather than that of the axes." On the other hand, in speaking of the Solani aqueduct, "a perfectly smooth, uniform channel, with perpendicular sides, and having no obstructions, either from bends or from irregularities of the bed, with a volume of water, nearly equaling 3000 cubic feet per second;" 85 feet wide, and over 900 feet long, 8·2 feet deep, and a bottom velocity of 2·60 to 3·80, averaging 3·47 feet per second, Mr. Login "found that a deposit of sand had actually taken place where the bottom velocity was three times what would be sufficient for transporting sand."

Before leaving this branch of the inquiry, the writer may offer a few reflections of his own. The traveler on the lower Mississippi floats upon a mighty river, from 2200 to 5000 feet wide, averaging about 3300 feet; from 70 to 180 feet deep, averaging about 115 feet; its velocity at the surface and in the thread of the current is about five miles per hour (about 7·5 feet per second); being a series of bends, some of them exceedingly sharp and sudden, there are produced the most violent irregularities of current; in the vicinity of a sharp curve, especially, there may be seen immense whirlpools, whose final actions and effects it would be impossible to follow to the end; but we know from observation that there are in such localities all sorts of under currents, exceeding the surface velocity, currents along shore, that run

up stream at the rate of 1 or 2 miles per hour, and similar anomalies. The wonder is not that such a river should erode its banks, but how it is that clay, fine sand and mud can at all contain it. On the other hand, every engineer who has been along the seacoast will have noticed places where the tide will run on the ebb at the rate of 2 and 3 miles per hour, 3 and 4·5 feet per second, *in beds of pure sand,* and yet such channels will not become deeper, but will often fill up, on the contrary, and narrow up without any apparent cause, gradually and slowly; they *diminish* their cross-section down to a certain limit, that is entirely unexplainable by theories of the action of the absolute velocity of the current alone, when speaking after the manner of Dubuat, as usually quoted; and reasoning from the result of experiments of this kind. But if attention be directed to the regularity of flow in such tidal streams, it will be noticed that they are generally quite shallow, running dry at low water, not infrequently, and that their flow is very regular and smooth, so that we have here a case of a very thin layer of sand moving from 5 to 10 miles in a year, according to Dubuat, that is, at the rate of about 0·0008 to 0·0017 feet per second. Whence it is explainable why such streams do not attack the bed of sand in which they flow to any appreciable extent.[1]

In an article in the "Annales des Ponts et Chaussées," 1868–1–34, on river navigation, by M. Fargue, Ingenieur des Ponts et Chaussées, and which, by the way, is unusually replete with facts and figures, the author comes to the conclusion that the shoals and pools and the scouring power of the section of river, fourteen miles long, under discussion, are regular functions of the situation and curvature of the bends of the river. His investigation seems to prove that a river will have the most regular and uniform depth of water when confined

[1] The cases here spoken of are not those of sand-bar formations, or similar cases, in which the action of the waves in throwing up sand forms an element of the problem. The impression is very clear in the writer's mind, that he has read somewhere, that in Holland, in the case of small channels leading across areas of mud-flats, the depth of these channels is increased, and they are maintained in the same situation by anchoring a row of casks along their centre line. If this is true, and the writer regrets not to be able to refer to the authority, when he may be mistaken about it altogether, the explanation would be that the ebb and flood currents cause whirlpools around the casks which deepen the channel under them, and the row of anchored casks thus makes and maintains a continuous fore-and-aft channel. Since writing this much, the writer has found a form of channel producing construction, composed of a row of small piles connected by a chain, described in the "Annales du Genie Civil," 1876–96. It is there translated from the Transactions of the Holland Society of Civil Engineers, and is highly commended. After successful operation in small channels, it was about to be tried on a large scale.

by artificial banks, whose curves consist of, and are joined to, the straight reaches by curves of the higher degree; or, if made of circular arcs, when they consist of compound curves, and whose tangents are those of what are called in mathematics osculations of the second and higher degrees instead of being simple tangents, as when a circle is drawn tangent to a straight line. He proposes to build a section of the river works, then about to be constructed upon this principle, and hopes to attain a more uniform depth of water by this means than he could otherwise expect. M. Fargue, similar to other writers which have been quoted, calls attention to the fact that "the ordinary hypothesis of the flow of water in parallel filaments, is absolutely inapplicable to the flow of rivers." And then goes on to show how the different portions of a river interchange places and penetrate each other.

Returning to a consideration of experiments made upon the power of currents to roll along materials, the year 1857 seems to have been the date of two sets of such. Mr. Thomas Login, M. Inst. C. E., in a short paper upon "The Floods of the Irrawaddy," printed in the "Proceedings of the Royal Soc. of Edinb., vol. 3, 1857, gives on page 475, the following table, reprinted in Stevenson's "Canal and River Engineering," 2d ed., page 315, as also in "Stevenson on Harbors," page 165. These experiments were made in a small laboratory trough, in a stream "seldom exceeding half an inch in depth." If we are to judge from the fact that Mr. Login, in the many articles which he wrote on the "abrading and transporting power of water" in 1867–69, seems never to have once alluded to these experiments of his own, of ten or twelve years previous, we should conclude that he did not value them very highly; a conclusion that would be confirmed by a study of the arguments of these later articles.[i] However, the following is the table:

MATERIALS.	Current required to move.	Rate of sinking in water.	
	FT. PER SEC.		
Brick-clay when mixed with water and allowed to settle for half an hour.	0·25	0·0095 !	Brick-clay in its natural
Fresh-water sand, . . . , .	0·67	0·17	state was not
Sea sand, ...	1·10	0·20	moved by a
Rounded pebbles, about size of peas, .	2·00	1·00	current of 2·1
Vegetable soil, ...	0·90	(?)	ft. per second.

[i] Min. Proc. Inst. C. E., 1867–68, p. 471; *The Artizan*, 1869–30, and a series of articles later in the same volume: *Engineering*, 1869–1–412 and 1869–2–133; *The Engineer*, 1869–1.

Table showing the Effect of Running Water in Moving various Substances.

Description of Object.	Weight in oz. avoir.	Cubic contents in ins.	Specific grav.	Velocity of Current.																
				0 to 1·00	1·00 to 1·25	1·25 to 1·50	1·50 to 1·75	1·75 to 2·00	2·00 to 2·25	2·25 to 2·50	2·50 to 2·75	2·75 to 3·00	3·00 to 3·25	3·25 to 3·50	3·50 to 3·75	3·75 to 4·00	4·00 to 4·25	4·25 to 4·50	4·50 to 4·75	4·75 to 5·00
Brickbat	22·0	18·5	2·05	......	......	......	......	......	......	......	......	start	0·94	1·15	1·25	1·30	......	2·14	2·31	......
	16·0	13·6	2·03	......	......	......	......	......	start	......	......	1·15	......	......	1·50	......	......	......	2·31	......
	9·0	7·33	2·12	......	......	......	......	......	start	0·7	0·82	......	1·20	......	......	......	1·87	2·00	2·61	......
	6·0	4·76	2·18	......	......	......	......	......	......	start	......	......	0·42	......	1·2	......	2·00	2·14	......	......
	3·0	2·59	2·00	......	......	......	......	start	......	......	1·00	......	......	1·50	......	......	......	......	......	......
	16·0	12·98	2·13	......	......	......	......	......	......	start	......	......	......	1·11	1·50	1·58	2·00	......	......	2·73
Building Stone (Oolite)	22·0	17·68	2·15	......	......	......	......	......	......	......	......	start	1·00	1·15	1·25	1·43	......	......	......	......
	9·0	6·70	2·32	......	......	......	......	......	......	......	start	0·91	......	1·15	1·20	1·25	1·87	......	......	......
	3·0	2·39	2·17	......	......	......	......	......	start	......	......	......	......	1·36	1·43	1·87	......	......	2·22	......
Chalk	22·0	18·54	2·05	......	......	......	......	start	......	0·60	0·67	......	1·20	1·30	......	1·67	......	1·76	......	......
	16·0	12·74	2·17	......	......	......	......	......	......	start	......	1·00	1·11	1·50	......	1·87	......	......	......	......
	9·0	7·78	2·00	......	......	......	......	......	start	......	0·93	......	1·36	......	1·87	......	......	......	......	......
	6·0	5·18	2·00	......	......	......	......	......	start	......	0·92	......	1·15	1·58	......	1·67	2·14	......	......	......
	3·0	2·39	2·17	......	......	......	......	......	......	start	0·75	0·94	1·03	......	1·77	......	......	......	......	......
Flints	16·0	10·37	2·67	......	......	......	......	......	......	......	......	......	start	......	1·00	1·06	......	1·56	1·84	......
	9·0	6·05	2·57	......	......	......	......	......	start	0·70	......	......	......	1·30	1·50	......	......	......	......	......
	6·0	4·11	2·52	......	......	......	......	......	......	start	......	0·87	......	......	......	......	1·46	1·58	......	2·00
	3·0	1·95	2·66	......	......	......	......	......	......	......	start	......	......	1·07	1·36	1·43	1·76	......	......	......
Coal	22·0	28·59	1·33	......	......	......	start	......	......	......	0·91	......	......	1·50	1·76	1·87	......	......	......	......
	9·0	11·69	1·33	......	......	start	0·54	......	......	1·11	......	......	1·67	......	......	2·07	......	......	......	......
	3·0	4·11	1·26	......	......	start	0·45	......	......	1·11	......	......	1·87	2·00	......	......	......	......	......	......
Clinkers	16·0	11·67	2·37	......	......	......	......	......	start	......	......	......	......	1·36	......	......	......	......	......	......
	9·0	6·05	2·57	......	......	......	......	......	......	......	......	start	......	......	......	......	1·15	1·50	......	......
	3·0	2·39	2·17	......	......	......	......	......	start	......	......	......	......	......	1·50	......	1·87	......	......	......
Copper Slag	6·0	3·46	3·00	......	......	......	......	......	......	......	......	......	......	start	......	1·07	......	1·67	1·76	......
	3·0	1·73	3·00	......	......	......	......	......	......	start	......	......	......	......	......	1·21	1·76	2·00	......	......
	1·5	0·86	3·00	......	......	......	......	......	......	......	start	0·79	......	1·11	......	1·76	......	2·00	......	......

Limestone	5·0	3·02	2·86							start				0·94	1·11		1·58	1·67		
	3·0	1·73	3·00								start			0·90			1·25		1·43	2·00
	1·5	0·86	3·00								start					1·00		1·25		
Oyster shells	2·87	2·60	1·91					start	0·29					0·94		1·57				
	1·12	0·86	2·24							start				0·38	0·86	1·12				
	0·50	0·33	2·63			start										1·50		1·76		
Slates	15·0	9·06	2·86									start				2·00			2·14	
	9·0	5·4	2·88										start						1·00	1·58
	4·0	2·38	2·90						start			0·68					1·43	2·00		
Nails																			start	
Scraps of Iron (small)										start										
Ginger Beer Bottle	18·87	14·50	2·25								start	1·87				2·14				
Glass Bottle (broken)	19·0	12·12	2·71								start				1·11	1·58				
Brick on dab of Clay																start	about	6·00		
Granite (broken)	6·50	4·22	2·66						start		0·65	1·00		1·15	1·25		1·76			
	3·0	1·94	2·67						start							1·00	1·44		1·87	
	1·50	0·97	2·66									start		1·11		1·30	1·50	2·00		
Boulders	11·87							start		1·08		1·30					1·53			
	5·87									start	1·11			1·67			2·14			
	3·31										start		1·50		2·00		2·31			
Sewage deposit			1·30			start														
Road Scrapings			1·78	start																
Gravel, ¼ inch			1·41			start														
" ½ inch			1·46							start										
Sand (yellow)			1·81	start																
" (green)			1·81	start																

NOTE.—The figures in the table show the velocities, in feet per second, with which the various substances moved after they had started.

The other set of experiments made in 1857 are those by Thos. E. Blackwell, civil engineer, as Commissioner on Metropolitan Drainage, in the "accounts and papers" for 1857, ordered printed August 3d of that year. The table of results is on page 167 of the Appendix. It is reprinted in Beardmore's "Manual of Hydrology," on page 7, but omitting twenty-two sets of experiments. Though it might be inferred from the text that these experiments were made in a stream four feet wide by three feet deep, yet the drawing shows the experimental portion to have been only about eighteen inches deep. The channel was sixty feet long, and was made of rough but painted elm plank; the velocities were carefully and skilfully measured, and the record has been transmitted in exceedingly complete shape, so that these experiments rank very high among their particular kind. Fifty-three kinds of materials were experimented on, and the table is the record of four hundred and twelve experiments. Says Mr. Blackwell: "These experiments allow the following inferences to be drawn: 1. For objects of the same character, the velocity required to start them, increased with the mass of the object. 2. For different objects the velocity increased with the specific gravity. 3. That according as the object assumed a form approaching a sphere, the less velocity it took to move it; whereas, a flat object, like slate, required a considerable current before it became disturbed from its position. And 4. As the velocity of the current is increased after an object is in motion, the velocity of such object increases in progressive ratio.

It is well to observe at once, that a velocity which will start an object will (when constantly maintained, and no accidental circumstances occur to prevent it,) never allow such object to deposit in the stream. Layers of the different objects were submitted to the action of the current, and the general results proved that the velocity required to remove them was considerably above that which would have been efficient in the case of a single object.

As a general conclusion, it may be observed that a velocity from 2 feet to 3·5 feet per second will remove all objects of the nature and dimensions of those that are likely to be found in sewers."

If the writer were to comment on these remarks, it would be to the effect that though the experiments do not, of course, disprove the very rational inferences above cited, and which would also result from careful *a priori* reasoning, they certainly show no regular laws of the

kind indicated. It would be impossible to evolve from them, for example, a formula showing the relations between mass and velocity, or between specific gravity and velocity. In saying this, no fault is intended to be found with the experiments, but it is said for the purpose of pointing out the want of regularity in the action of currents of this kind and under such circumstances. The experiments were made to test whether, and they prove that "a velocity from 2 feet to 3·5 feet per second will remove all objects of the nature and dimensions of those that are likely to be found in sewers." Further than this, little can be concluded from them.[1]

An interesting point that seems to have been overlooked by experiments on artificial channels, or which they have as yet been unable to experiment on, is the effect of the inclination of the bed on which the materials to be rolled along are resting. In all the experiments made, this seems to have been very nearly horizontal, and such would be, approximately, the beds of all water-courses to which the experiments may be made to apply. But it is different with the *banks* of canals, and it is very conceivable that they would be easier affected by a simple straight current than the bottom of a canal or river, and that the current would cause certain portions of these banks to slide down to the bottom. We know, indeed, that waves have been observed to have an effect of this kind. In the Min. Proc. Inst. C. E., 1866–67, in the discussion on the use of steam power on canals, also quoted in Stevenson's "Canal and River Engineering," page 24, it is stated that on the Gloucester Canal, after the introduction of steam towage, the waves and other commotion in the canal (that were a result of the increased speed of the vessels passing through) caused the soft mud, which had formerly collected on the banks, to slide down these slopes, and kept them clean; in this case proving a benefit, for it had formerly been difficult to remove this mud with the dredge, for fear of injury to the banks; but the dredge could dig it up without such fear from the bottom of the canal.

There remain a number of data to be mentioned, having reference to the size and the behavior of materials as actually found in the

[1] For the benefit of American readers, attention should be called to the fact that the oyster-shells spoken of in the table are puny little things, 2·5, 3, and 3·5 inches long. To move a "Stony Creek" or other prime oyster-shell, 9 or 10 inches long or more, would probably bother most sewer velocities.

beds of streams. On page 473, Min. Proc. Inst. C. E., 1867–68, Mr. Thomas Login says: "Experience on the Ganges Canal has shown that this (to have the deposits balanced by the abrasions) requires a mean velocity of about 3·75 feet per second, with a surface slope of a little less than fourteen inches in the mile." And on page 479, Mr. Login gives a "table showing approximately the sections and slope probably best adapted to irrigation canals and water-courses for Northern India." Coming as it does from a gentleman of long experience in this particular branch of the profession, it is entitled to serious consideration, to say the least. It is for each engineer to note the wide difference between the data given by Mr. Login and those derived from the trough experiments of Dubuat, and to decide to which he proposes to give the greater weight.

The following is the table above referred to:

TABLE

SHOWING APPROXIMATELY THE SECTIONS AND SLOPES PROBABLY BEST ADAPTED FOR IRRIGATION CANALS AND WATER COURSES FOR NORTHERN INDIA.

Cubic feet of discharge per second.	CALCULATED SECTIONS.					PROPOSED SECTIONS.			Side slopes of channels.	REMARKS.
	V, Mean velocity ft. per sec.	*H*, Hydraulic mean depth.	Breadth of channel at bottom.	Depth of water with full supply.	Slope of surface of water. Inches per mile.	Breadth in feet at bottom.	Depth in feet with full supply.	Slope of water surface, full supply.		
CU. FT.	FT.	FT.	FT.	FT.	IN.			IN.		
50	2	2	2½	4	15	2	4½	16½	1 to 1	Calculated on Beardmore's formula: $\frac{11\sqrt{H \times S}}{12} = V,$ where: H = Hydraulic depth in feet. S = Fall in ft. of surface of water per mile. V = Mean velocity in ft. per sec. In no case should the mean velocity exceed 4 ft. per sec, 3¾ probably being the safe limit, and not less than 2¾ ft. for the main channels. Keeping in mind that the greater the velocity, the cheaper the section in deep digging.
100	2¼	2½	4½	4¾	14½	4	5¼	16	1 to 1	
250	2½	3⅓	15	5	13½	13½	5½	14⅚	1 to 1	
500	2¾	4¼	27½	5½	13	25	6	14⅓	1 to 1	
1000	3	5	50	6	13	45	6⅔	14⅓	1 to 1	
2000	3¼	6	77½	7	13	70	7¾	14⅓	1½ to 1	
3000	3½	7	95	8	12¾	85	8⅘	14	1½ to 1	
4000	3½	7½	121½	8½	12¾	110	9⅓	14	1½ to 1	
5000	3⅔	7⅔	147½	8½	12½	130	9⅓	13¾	1½ to 1	
6000	3¾	8	170	8¾	12½	150	9⅔	13¾	1½ to 1	

On page 509 Mr. Login gives these additional data concerning the Ganges Canal.

No. of mile.	Point of observation.	Mean velocity. Ft. per sec.	Discharge. Cu. ft. per sec.	REMARKS.
1st.	Below the Regulator near Hurdwar.	5·10	6710	At the Regulator the water was 9 ft. deep. The bed was composed of pebbles, and had a slope of 2 ft. per mile, the water was quite clear.
19th.	Over the Solani Aqueduct at Roorkee.	4·48	6283	The depth of the water over the floor of the aqueduct was 8·25 ft. The water was slightly turbid.
50th.	At the head of the Futtigurh Branch above the Regulator.	3·46	5279	There was silt on the floor of the Regulator, and the water was very turbid.

And on page 544, Mr. J. T. Harrison, M. Inst. C. E., gives the following:

Name of River or Canal.	Length of Canal in Miles.	Fall per Mile.	Velocity. Ft. per sec.	Velocity. Miles per hour.	Discharge per day, in Gallons.	Remarks.
		IN.				
Ganges Canal to Nanoon..........	180	....	....	....	....	....
Cawnpore Branch	170	14	3·75	2·2	2,700,000,000	....
Etawah	180	....	....	....	....	....
Ditto..............	....	17	....	3·0	....	Dangerous cutting bed.
	....	15	....	2¾	....	Slightly "
	....	13·8	....	2¼	....	Silting up.

On page 545, Mr. Login observed "that the slope of the Ganges Canal was originally projected at fifteen inches in a mile, and the calculated velocity of the current was four feet per second. In the year 1860, when he took charge of the works, the surface slope exceeded sixteen inches, with a mean velocity of 4·5 feet per second, and the bed was being eroded to a dangerous extent; this he had reduced to about fourteen inches in the mile, and the mean velocity

of the stream had fallen to 3·75 feet per second. With this reduced velocity the bed began to silt up, and it had continued so for the last five years; therefore, he believed the proper slope and velocity had been obtained."

On page 541, Mr. Harrison states: "The Thames in some parts afforded an excellent illustration of the importance of maintaining sufficient inclination and velocity to enable the river to carry off mud. He had found that for several miles above Oxford the natural fall of the Thames valley was about fourteen inches in the mile, the minimum inclination at which, apparently, in this country as in India, large rivers could carry off mud. The river Thames formed a winding channel through this valley of deposited mud; by the introduction of locks, the inclination was reduced from fourteen inches to eleven inches per mile, consequently a considerable part of the Thames above Oxford was silted up, so that a boat drawing eighteen inches of water could not pass up the river."

In the article by M. Fargue, in the *Annales des Ponts et Chaussées*, 1868, already mentioned, it is stated that the mean width of the Garonne, near Langon, is about five hundred and ninety feet. At low water the slope is about sixteen inches in the mile, though as much as eighty-nine inches to the mile in some places. The depth averages about ten or eleven feet. On an average of twenty-six years there were:

66·5 days of low water in each year,
195·0 days of mean water,
81·0 days of "bank full,"
20·8 days of ordinary freshet,
1·7 days of extraordinary freshet.

During these twenty-six years the average discharge was about 25,000 cubic feet per second (about 687 cubic metres), whence, as a grand mean for twenty-six years and for all depths, the velocity would average about four feet per second.

The stretch of river under examination was about fourteen miles long, and the bed of this portion of it consisted of pebbles from 2·0 to 3·4 inches in diameter, mixed with thirty-three to fifty per cent. of sand. It had been in a virtually constant condition for twenty odd years.

RESULTS UPON THE RHINE.

Miles below Basel.	Pieces of gravel to the foot: $= p^3$ pieces, in one cubic foot.	Weight of largest piece. Lbs.	Velocity: Feet per second, at high water.	Slope in inches per mile.
2·5	8·4	13·5	12·	63·
20·0	10·7	10·5		
34·5	11·5	6·4		
58·5	?	4·9		
90·0	12·4	3·3	10·	39·
115·0	16·9	2·2	8·	25·
165·0	18·1	0·2	Aver. 5·	Aver. 9·

Professor Henry Sternberg, Director of the Polytechnic School of Carlsruhe, and a practicing engineer for fifteen or twenty years until he became professor in 1862, in an article in the Berlin *Zeitschrift für Bauwesen* for 1875, page 495, on the "Profiles and cross-sections of rivers bearing gravel," gives the foregoing table (the original in metric measures) of data concerning the Rhine, from Basel to Mannheim. Some data of slope and velocities are added, taken from a historical account of the improvement of this portion of the Rhine, published by the Engineering Department of the Grand Duchy of Baden. The Rhine flows on this length of one hundred and sixty-five miles, mainly between artificial banks, from two hundred and forty to three hundred metres, seven hundred and ninety to nine hundred and eighty feet apart; its maximum depth is about twenty-nine or thirty feet; average depth about sixteen or seventeen feet.

Finally, J. Schlichting, an engineer of the Prussian government, in charge of works upon the Memel, in the same journal for 1877, page 86, in mentioning Prof. Sternberg's article, says: "The mean velocity at the bottom of the Memel, as derived from the current measurements taken in five cross-sections, varied from 1 foot to 1·6 feet per second. On this part of the river the bed consists of fine sand, 'pin gravel,' and pebbles of the size of a pea, all mixed up; occasionally, larger pebbles are found, the size of a bean, say. This sand, pin gravel, and pebbles remain in constant motion, even at low water stages of the river, as may be inferred from the continual

changes in the channel and the shoaling up of portions of it. This last operation is often completed in a few days, whence it may be inferred that the velocity of motion of these materials is quite appreciable." If it may be permitted to point out the somewhat curious course of reasoning in these sentences, the writer would call attention to the circumstance that the facts stated prove the deposit or cessation of motion of the materials on the bottom of the river, quite as much as they do that of their continuous movement. In other words, a bottom velocity of 1 to 1·6 feet per second, corresponds to a general movement of sand, pin gravel and pea pebbles, but it also corresponds to a deposit of the same class of materials. Or are we to infer that shoaling and scouring are in equilibrium at these velocities?

This case very well illustrates the difficulty of expressing a complex relation of this sort in figures. As an additional illustration, it may be instructive to consider the following table, compiled from data that have been given in this paper.

Diameter of pebble in inches or as described.	AUTHORITY.								
	Funk. Large rivers.		Dubuat. Trough expts.	Umpfenbach Small brooks		Login. ½ in. depths.	Blackwell. 48 × 18 inches of channel.	Sternberg. River Rhine.	
	Surface veloc. observed.	Bottom veloc. calculated.	Bottom veloc. rudely measured.	Surface veloc. observed.	Bottom veloc. calculated.	Bottom veloc. measured.	Bottom veloc. measured.	Surface veloc. observed.	Bottom veloc. calculated.
	PEBBLES MOVE WHEN VELOCITY IS IN FEET PER SECOND.								
Pea size.			0 67			2·0			
0·25							1·25 to 1·50		
0·5							2·25 to 2·50		
0·67								(5·0)	3·0
1·00			2·00	(3·1)	2·5				
1·5			3·00					(10·0)	6·2
2·0	(5 6)	3·1		(5·2)	4·0				

The conclusions of the writer may be summed up in the following paragraphs:

I.—Water, when in motion, acts or tends to act upon its channel in two ways. 1. By direct friction, tending to drag materials along

its bed, or down its banks, if these have a sufficiently steep side slope; and 2. By lifting up materials, holding them in suspension, and thus carrying them along in the body of the current.

1. It is difficult to determine at what velocities any one kind of material will commence to move by direct friction of the water. It must depend on the specific gravity of the material, on the shape of its individual parts, on the nature and inclination of the bed it is to roll on, and to measure this velocity with any accuracy, the moving water must be free from all whirlpools or other relative motion of its particles among themselves, tending to lift up and carry off the material with which the experiments are being conducted. The effect of the simple friction of a stream of water upon its bed and banks is not a source of danger; its action is very slow, and it has never been shown to be of a dangerous character in any instance. It is apt, however, to produce shoals, similar to submerged, moving dunes (as in the Wisconsin River, above referred to), and thus to obstruct navigation, in the case of clear water rivers, flowing in a sandy bed, and in time of low water.

2. The exact force and other determination of the inner movements of the particles of water among themselves which abrade and erode banks and beds, lift up and transport materials, defies calculation or expression by formulæ in the present, or any at present conceivable state of hydraulic science. The effect of these inner movements must remain a matter of judgment in every especial case.

II.—For either kind of motion, and for every amount of it, there is a limiting size of individual objects of a certain specific gravity which will no longer be affected by such motion; therefore, just so soon as the beds and banks of a water-course are covered with bodies of this size and quality, those smaller and lighter having been washed away or covered up, the bed and banks must remain permanent.

Trouble, by reason of too much erosion, seems to have been confined, generally, to cases of undermining bridge piers and similar masonry or other structures placed in running water; the remedies for too much erosion have been either to diminish the velocity, and at the same time with it the relative motion of the particles of water among themselves, or the latter alone, by taking pains that the flow of the stream shall be as smooth, regular and uniform as possible; or

else to protect the parts that suffer from erosion by stone pitching, fascines, and by similar well known kinds of covering.

Trouble, by reason of the shoaling up of channels, has been remedied by stopping the erosion, whence comes the material which was being deposited; this called for the same remedies, therefore, as the difficulty last considered. But when it was a case of the shoaling up of a canal, fed from a silt bearing river, or any similar case, in which the erosion of material could not be prevented, then reliance had to be placed upon an opposite course of treatment, and by an increase of absolute and of relative velocity, the scouring had to be increased until there was a balance between the tendencies to deposit and to deepen; or if it was the case of a river, shoaling from the effect of simple friction of the water on its bed, or a river in which considerations of high and low water volumes, and other such considerations, prevented the application of remedies proper enough in a canal, but inapplicable to the case in hand, the engineer may have arrived at a conclusion often reached before, namely: that the difficulty was one to be avoided rather than remedied. A scheme of "slack-water navigation," by means of fixed or movable dams, or a lateral canal, would then take the place of a river improvement. It would result from these considerations that canals are easier managed than rivers; and canals that carry clean water naturally are easier managed than those that come already loaded with silt into that part of their channel which is to be taken care of.

It has often been spoken of as a curious freak of nature that brooks and rivers running through low lands should still further diminish their fall per unit of length by forming curves and serpentines; but if it is true that curves and bends are the most potent cause of whirlpools, and other such commotions of the water that rivers are subject to, and that these commotions are the prime agencies in the abrading and transporting power of these rivers, then this matter has the appearance of a very beautiful feature in the economy of nature. For by no other known means could these rivers acquire this power of abrading and of transporting matter, and thus enabling themselves to maintain their channel and their very existence.

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